A COMPARATIVE EVALUATION OF ‘HASS’ TYPE AVOCADO CULTIVARS ON POSTHARVEST PERICARP COLOUR DEVELOPMENT AND CORRELATION WITH SOFTENING: A CASE OF 'HASS', 'MALUMA-HASS' AND 'CARMEN-HASS'

BY

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PROF TP MAFEO

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DECLARATION

I, Kagisho Florence Ledwaba, confirm that the mini-dissertation submitted to the University of Limpopo for the Master of Science in Horticulture has not been submitted by me for any degree at this or other university.

.... 19/05/2025

Ms KF Ledwaba Date

DEDICATION

To my mother, Irene Ledwaba, whose love and sacrifices have shaped my path, and to my, siblings Avrol Ledwaba, Mpho Ledwaba, Lebogang Ledwaba and Mmasabatha Ledwaba, for your unwavering support and encouragement. I dedicate this work to you.

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ABSTRACT

During ripening, 'Hass' avocado fruit change colour from green to purple/black. However, early-season fruit exhibit a poor colour development, and this issue has not been studied in 'Carmen-Hass' and 'Maluma-Hass' when compared with traditional ‘Hass’ fruit. Therefore, the objective of this study was to compare the postharvest exocarp colour change for 'Carmen-Hass' and 'Maluma-Hass' avocado with 'Hass' and evaluate their correlation with fruit softening. The early-season fruit were harvested from a commercial farm, thereafter transported to the laboratory for further storage and analysis. At harvest, avocado fruit were assessed for dry matter content, whereas visual and objective colour parameters, firmness, and chilling injury were assessed during 12 days of ripening. The results showed that 'Carmen-Hass' avocado fruit exhibited the highest dry matter content at harvest when compared with 'Hass' and 'Maluma-Hass' cultivars. Furthermore, 'Carmen-Hass' fruit showed the highest visual colour change during ripening, followed by 'Maluma-Hass' after 12 days of ripening. All cultivars exhibited a decrease in lightness (L*) values throughout the ripening period, with 'Carmen-Hass' showing the most pronounced change between days 2 and 4 of ripening. A decrease in chroma (C*) values was observed across all cultivars throughout the ripening period, with 'Maluma-Hass' displaying the lowest C* values from day 8 to 12. There was a notable decrease in hue angle (*h°*) for all the cultivars throughout the ripening period, with 'Maluma-Hass' showing the most significant decrease from days 6 to 8. With respect to firmness, the three cultivars showed a decrease in firmness during ripening indicating that 'Carmen-Hass' softened the quickest, followed by 'Hass', while 'Maluma-Hass' retained firmness the longest. The 'Carmen-Hass' cultivar exhibited the lowest chilling damage, followed by 'Maluma-Hass', while the highest chilling index was recorded on 'Hass' fruit. In 'Carmen-Hass', firmness was highly negatively correlated with visual colour ($R= -0.942$, $p < 0.01$) and greenness ($R = -0.904$, $p < 0.001$). There was also a highly positive correlation between firmness and peel colour lightness ($R= 0.859$, $p < 0.001$) and chroma ($R= 0.79$, $p < 0.001$) as compared with 'Hass ' and 'Maluma-Hass'. In conclusion, 'Carmen-Hass' showed improved colour (black) development during ripening when compared with 'Hass' and 'Maluma-Hass' fruit. The findings suggest that all ‘Hass’ type avocado cultivars ripen

and their firmness decreases during storage. However, there was a significant difference in their exocarp colour change.

CHAPTER 1: GENERAL INTRODUCTION

1.1. Background

In recent years, the South African Avocado industry has experienced significant growth in the production and export of its fruit. Approximately 45-50% of the country's annual avocado production is exported, mainly to European markets (SAAGA, 2023). Globally, South Africa is ranked as the eighth largest exporter of avocado, after Mexico, The Netherlands, Peru, Spain, Chile, the United States, and Kenya. The 'Hass' cultivar is the most common commercial avocado cultivar globally due to its colour change during ripening, appealing flavour, texture, longer shelf-life; and therefore, a better economic return (Bill *et al*., 2014; Magwaza and). However, the peel colour change quality parameters have been inconsistent for some consignments of 'Hass' avocados imported from South Africa, raising concerns regarding their internal quality and consistency (Mathaba *et al*., 2015). The exocarp colour change from green to black or dark purple is specific to certain avocado cultivars like 'Hass'. Among these cultivars, 'Maluma-Hass' and 'Carmen-Hass' are the newly developed 'Hass' type avocado cultivars that have recently gained popularity. They exhibit characteristics similar to those of traditional 'Hass' by changing their exocarp colour during ripening. This colour change is due to chlorophyll degradation and an increase in anthocyanin pigments, which result in a purple-to-black colour during ripening. According to Cox *et al*., (2004), anthocyanidin 3-*O*-glucoside is the main anthocyanin responsible for exocarp colour change, thereby yielding a 'Hass' avocado fruit's attractive colour.

1.2. Problem statement

According to recent studies, a quality problem was observed in 'Hass' avocado fruit, which is the de-synchronization of colour change with softening. This resulted in poor exocarp colour development causing confusion among consumers when the fruit reaches a ready-to-eat state (Mathaba *et al.,* 2015, Mathaba *et al*., 2017; Mathe *et al*., 2017). This incidence may lead to logistical problems for marketers, inconsistency in quality delivery to consumers and increased fruit losses (Pedreschi *et al*., 2014), especially in lucrative high-quality export markets. Various factors like growth temperature, slope of the orchard, harvest time, and postharvest conditions influence the occurrence of colour change de-synchronizing with softening during ripening in' Hass' avocado fruit (Hernández *et al*., 2016). However, it is unclear whether the newly introduced 'Maluma-Hass' and 'Carmen-Hass' cultivars have colour de-synchronization with softening as reported in traditional 'Hass' fruit.

1.3. Rationale

The marketing of 'Hass' avocado fruit relies heavily on colour change (Naamani, 2011). However, consumer acceptance is compromised if colour development targets are not met during ripening. If there are issues in the colour development of 'Hass' avocado fruit, there could be a considerable (up to 37%) loss in profit for 'Hass' cultivars, and consumers may lose confidence in the fruit. Farmers aspire to reach the market early and sell their avocado fruit at premium prices. Nonetheless, early-season avocado fruits present a colour softening de-synchronization challenge (Mathaba *et al*., 2015).

The desire for farmers to export early is to get their products to the market while they can still be sold at a premium price. The problem lies in the colour change of the early-season 'Hass' avocado fruit, which does not synchronize peel colour with softening. This means that the fruit may soften, with minimum colour changes to the exocarp. This de-synchronization of peel colour and softening creates difficulties in gaining consumer acceptance (Hernández *et al*., 2021). According to Mathaba *et al*. (2016) and Arancibia-Guerra et al. (2022), the issue of de-synchronization has been previously studied mainly in traditional 'Hass' cultivars and the outcomes validated that colour change de-synchronization with softening is predominant in early-season fruits. However, with the growing demand for newly developed cultivars, exporting them without understanding their behaviour during the early season could lead to rejection. The lack of information on how these new cultivars behave based on this parameter when compared with the traditional 'Hass' cultivar may pose a challenge for export markets.

1.4. Aim

This study aimed to profile, for the first time, the postharvest exocarp colour development pattern of 'Maluma-Hass' and 'Carmen-Hass' when compared with traditional 'Hass' avocado fruit during ripening.

1.5. Objective

•To determine if there are any significant differences in the exocarp colour development between traditional ‘Hass’ avocado fruit and two new Hass-type cultivars ('Maluma-Hass' and Carmen-Hass') during ripening.

1.6. Null hypothesis

•The exocarp colour development of traditional ‘Hass’ does not differ from that of the two new cultivars ('Carmen-Hass' and 'Maluma-Hass') fruit during ripening.

1.7 Structure of the study

Chapter 1 provided an overview of the study covering the background, problem statement and research motivation. It also outlined the study’s purpose, objectives, and key hypotheses. Chapter 2 focuses on a literature review, emphasizing both national and international studies related to pre-harvest and postharvest factors influencing exocarp colour development in ‘Hass’ avocado cultivars. Chapter 3 detailed the research methodology, covering the study design, production area and harvest time, method of collecting data and analytical techniques. The findings and discussion of the results were presented in chapter 4. Finally, chapter 6 provides a summary of the study, along with recommendations based on the research findings.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

In 'Hass' type avocado fruit, black or purple colour development is due to the presence of anthocyanin pigments, and cyanidin-3-*O*-glucoside has been particularly identified and quantified in 'Hass' avocado fruit (Cox *et al*., 2004). The colour development of 'Hass' avocado fruit, which varies considerably over maturity stages and ripening temperature, is a key sign of ripeness and is considered an important quality indicator (Mathaba *et al*., 2015). Therefore, poor colour development and downgrading of 'Hass' avocado fruit can be attributed to low anthocyanin concentration during ripening. In 'Hass' avocado fruit, there are several factors that influence anthocyanin accumulation during ripening such as temperature, production region, orchard site, fruit canopy position, fruit size, presence of seed and occurrence of physiological disorders (Mathaba *et al*., 2015; Mathaba *et al*., 2016; Mathaba *et al*., 2017; Shikwambana *et al*., 2021). Therefore, understanding these influencing factors is important for improving the colour development and quality of the fruit.

Numerous studies have been conducted on colour development of 'Hass' avocado fruit during ripening. However, little is known about its hybrid cultivars including 'Maluma-Hass' and 'Carmen-Hass'. Avocado 'Hass' and its hybrid cultivars 'Maluma-Hass' and 'Carmen-Hass' have distinct harvest seasons. The 'Hass' harvest season is from May to October, while 'Maluma-Hass' is from March to July and for 'Carmen-Hass', the harvest season is several weeks earlier than 'Hass' avocado. In this chapter, we discuss the processes, preharvest and postharvest factors that regulate anthocyanin synthesis, accumulation and softening in black-skinned avocado cultivars. Due to limited studies, we refer to the extensive literature available on the colour development and ripening of 'Hass' avocado.

2.2. Avocado Cultivars

Table 2.1: A comparison of key characteristics of 'Hass' type avocado cultivars ('Hass', Maluma-Hass and Carmen-Hass), including differences and similarities in origin, maturity season, fruit shape, exocarp properties and fruit and seed size, moisture content. Flesh attributes, and susceptibility to lenticel damage.

Characteristics	'Hass'	'Maluma-Hass'	'Carmen-Hass'
Origin	South California,United States of America	Levubu, Limpopo, South Africa	Michoacan, Mexico
Genetic background	Guatemalan Mexican hybrid	Predominantly Guatemalan with some Mexican genes	Guatemalan Mexican hybrid
Maturity season	March-May	November	May-September (with off season crop: November to December)
Fruit shape	Obovate	Pyriform	Ovate/egg shaped, rounder
Exocarp apperance	Dull	Shiny	Shiny
Skin texture	Semi-rough, pebbly, leathery	Rough textured	Smoother
Skin thickness	1-2 mm	1-2 mm	1-2 mm
Seed size	20-25% of fruit volume	10-15% of fruit volume	Medium to large
Fruit size	170 t0 400 g	150-400 g	170-350 g
Moisture level	≤78%	≤77%	≤75-78%
Flesh colour	Creamy yellow with light green rind	Creamy yellow with light green rind	Creamy yellow with light green rind
Flesh texture	Smooth almost no fibres	Smooth, no fibers	Smooth, almost no fibers
Taste	Excellent, Rich creamy and nutty	Excellent, rich, creamy	Excellent, rich, creamy and nutty
Lenticel damage susceptibility	High (more susceptible)	Less susceptible	Less susceptible
Reference	(Tan *et al*., 2017)	(Ernst *et al*., 2015; Kruger *et al*., 2017	(Illsley-Granich *et al*., 2011; Rosas *et al*., 2016)

2.3 Ripening physiology of avocado fruit

The ripening physiology of avocado fruits at post-harvest is a complex process influenced by various factors, including ethylene synthesis and exposure, seed presence, and environmental conditions. Ethylene, a plant hormone, plays an important role in the ripening of avocado fruit. Studies have shown that prolonged exposure to ethylene accelerates ripening, as evidenced by increased respiration rate and fruit softening

(Zauberman *et al*., 1988). As the temperature increases, the enzymes involved in ethylene biosynthesis are activated (Tucker *et al*., 2017). During this process, S'-adenosylmethionine (SAM) is converted to 1-aminocyclipropane-1-carboxylic acid (ACC) by ACC synthase, which is further converted to ethylene by ACC oxidase. This leads to an increase in the respiration rate until it reached the maximum climacteric peak, and thereafter decreases. Villa-Rodríguez *et al*. (2011) discovered that ethylene production increased with ripening temperatures ranging from 20 to 25°C, whereas temperatures above 25 to 40°C inhibited ethylene production due to the inactivation of the key enzymes ACC synthase and oxidase involved in ethylene biosynthesis.

Additionally, it has been noted that ethylene accelerates fruit ripening by increasing the activity of enzymes responsible for fruit firmness, such as polygalacturonase (PG), pectin methylesterase (PME), and cellulase which lead to the degradation of the cell wall, thus softening the fruit (Goulao and Oliveira, 2008; Sierra *et al*., 2019). These enzymes are crucial for avocado softening and play a significant role in the ripening of many fruits, including the 'Hass' avocado. Typically, softening occurs synchronously with the colour changes. However, research has revealed that early-maturing 'Hass' avocados exhibit de-synchronization in colour change and softening (Mathaba *et al*., 2015). Avocado fruits are harvested when they are mature but not yet ripe, and the ripening process only starts after removal from the tree (Pinto *et al*., 2019). During this process, the avocado fruit undergoes several physiological and biochemical changes, including biosynthesis and accumulation of pigments, such as anthocyanins, lipids, vitamins, and antioxidants (Donetti and Terry, 2011). After harvest, Hass' avocado fruit are green and firm, but as ripening progresses, their colour changes from green to dark purple or black, accompanied by a softening (Cox *et al*., 2004). In 'Hass' avocado fruit, colour change is influenced by various factors, including the level of maturity, seed maturity, ripening temperature, fruit size, postharvest treatment, and occurrence of chilling injury.

Mathaba *et al*. (2015) found that 'Hass' avocado fruit harvested early-season did not reach the desired exocarp colour during ripening compared to those harvested in the mid- or late season. This is because there is usually competition for sugar (glucose) accumulation between the seed and the exocarp of early harvested 'Hass' avocado fruit, which results in less accumulation of anthocyanin in the exocarp during ripening. In contrast, late-season fruit have mature seeds and no longer compete, allowing for better colour development (Mathaba *et al*., 2017). Increased commercial maturity is associated with increased fruit size, oil and dry matter content, and decreased ripening times (Magwaza and Tesfay, 2015; Yahia and Woolf, 2011).

2.4 Peel colour

Fruit colour is one of the important quality parameters that influence consumers' perspective (Omelas-Paz *et al*., 2008). Colour development in 'Hass' avocado during ripening serves as a visual indicator of ripeness (Cox *et al*., 2004). Studies have shown that 'Hass' avocado fruit differs from other fruit crops in colour development, as their colour change occurs at the post-harvest stage. The peel of 'Hass' avocados transitions from green to purple or black as they ripen, making it easier for consumers to assess their readiness to eat. These visual changes can also be objectively quantified using colour measurements.

Objective colour measurements are performed using a chromameter based on the CIELAB colour system, which evaluates parameters such as L* (lightness), a* (greenness), b* (yellowness), C* (chroma or colour intensity), and h^o (hue angle). The L* value ranges from 0 (black) to 100 (white), hue angle (h^o) describes the overall colour tone, while chroma (C*) and hue angle are derived from the a* and b* values (McGuire, 1992). During ripening, the L*, C*, and h^o values of 'Hass' avocados decrease as the peel darkens from green to purple or black, driven by the degradation of chlorophyll and the synthesis of anthocyanins and carotenoids (Cox *et al*., 2004; Nambi *et al*., 2016).

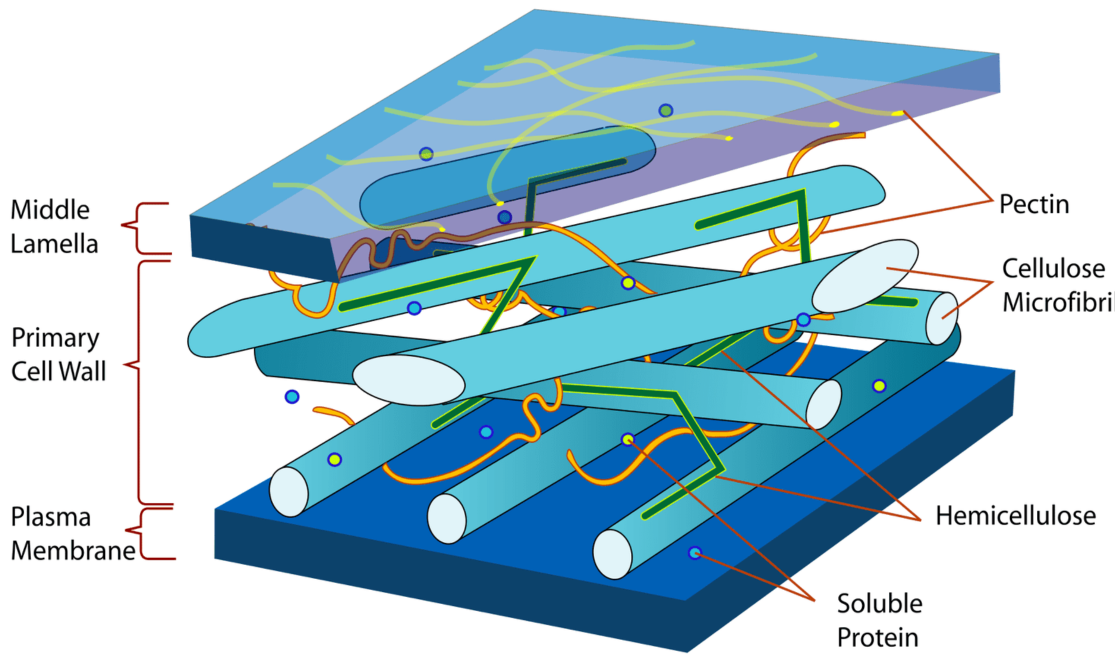
The a* value, which indicates the green-to-red spectrum, increases from a negative value (green) to a slightly positive value as ripening progresses in 'Hass' avocado (Sierra *et al*., 2019). This shift reflects chlorophyll breakdown and the accumulation of anthocyanins and carotenoids, which contribute to a reddish colour. Conversely, the b* value, representing the blue-to-yellow spectrum, declines during ripening. This decrease results from the breakdown of chlorophyll a, which reduces green intensity and enhances the visibility of yellow pigments like carotenoids (Sierra *et al*., 2019). Ripening conditions, such as temperature, influence these changes, with high temperatures accelerating the process and low temperatures slowing it. Studies by Maftoonazad and Ramaswamy (2008) and Marquez *et al*. (2014) highlight that the changes in L*, a*, b*, C*, and h^o values follow a well-documented pattern, making them reliable indicators of ripening stages and fruit quality.

2.5. Fruit softening

During avocado ripening, significant changes occur in the colour and firmness (García-Rojas *et al*., 2016). This is due to metabolic events that lead to softening of the avocados' mesocarp tissue as they ripen. These events include loss of cellular turgor pressure caused by osmotic solute accumulation in the apoplast, degradation, physiological changes in membrane composition, starch breakdown, and alterations in the cell wall structure (Defilippi *et al*., 2018).

The changes during softening are primarily due to the dissolution of the middle lamella, leading to a reduction in intercellular adhesion and thinning of the cell wall. (Liu *et al*., 2021). Pectins play a crucial role in regulating cell-to-cell adhesion as they are the most abundant polysaccharides in the cell wall matrix and middle lamella (Figure 5). Although pectin-degrading enzymes are mainly associated with fruit softening, other enzymes acting on glycan polysaccharides and cellulose microfibrils also contribute to this process. Polygalacturonase, pectin methylesterase, β-galactosidase (β-GAL), and pectate lyase are enzymes that act on different components that contribute to fruit softening.

Polygalacturonase (PG) and pectin methylesterase (PME) are the main pectin-degrading enzymes found in fruits. PME catalyzes the removal of methyl groups from Homogalacturonan (HGA), whereas PG cleaves the galacturonic linkages of the HGA backbone. The high levels of PG activity observed in avocado have been related to the extensive solubilization and depolymerization of pectins that occur during avocado ripening (Huber *et al*., 2002). In contrast, several studies have suggested that HGA, which is present in a highly methyl esterified form in the cell wall, is more susceptible to PG activity if partially de-esterified (Levesque-Tremblay *et al*., 2015). The role of de-esterification of HGA is attributed to PME activity in many fruits, including avocados.



2.1 Cell wall structure of a plant

2.6. Maturity, moisture content (MC) and dry matter (DM)

Harvest maturity of avocado fruits is a critical determinant of postharvest quality, including colour development. Moisture content (MC) and dry matter (DM) are commonly used indices to assess the maturity of avocados, with a direct impact on the fruit ripening process and colour change (Magwaza and Tesfay, 2015; Olarewaju *et al*., 2016). Studies have shown a significant relationship between DM and oil content (OC), which in turn correlates with fruit colour parameters. For instance, in the Colombian context, non-destructive indicators, such as fruit colour, were linked to DM, suggesting that colour could be a potential maturity indicator (Rodriguez *et al*., 2018). Similarly, research on 'Hass' avocado indicated that DM content, skin colour, and pulp hue angle increased with harvest date and ripening degree (Osuna-García *et al*., 2010). These findings suggest that as avocados mature and DM accumulates, colour parameters change, marking the progression of ripeness. However, there are contradictions in the literature regarding the direct effects of MC and DM on colour development. While some studies have found a highly linear relationship between DM and MC, which is related to colour, others have reported that the fruit aspect in the canopy has no effect on the percentage of DM or colour development (Hofman and Jobin-Decor, 1999; Rodriguez *et al*., 2018). This indicates that although there is a general trend, other factors, such as fruit location and environmental conditions, may also play a role in colour development. The literature suggests that harvest maturity, as indicated by MC and DM, has a significant effect on avocado fruit colour development. The relationship between DM and OC and their association with colour parameters underscores the importance of these indices in determining the optimal harvest time for avocados to ensure desirable colour and ripeness.

2.7. Research gap

Early-season 'Hass' avocados often face challenges with their exocarp colour development during ripening, which affects fruit quality and consumer preference. This issue has been noted in previous studies, where the colour change did not synchronize with the softening of the fruit, leading to confusion among consumers regarding the fruit's readiness to eat. Consequently, consumers may make incorrect purchasing decisions (Mathaba *et al*., 2015, Mathaba *et al*., 2016, Mathaba *et al*., 2017, Mathe *et al*., 2017). However, only preliminary description of the problem has been studies in early 'Hass' and not in the newly developed cultivars such as 'Maluma-Hass' and 'Carmen-Hass'.

2.8 Chapter overview

The literature reviewed the processes, preharvest and postharvest factors that regulate anthocyanin synthesis, accumulation and softening in black-skinned avocado cultivars. It highlighted the key factors influencing the ripening and colour development of 'Hass' type avocados. While cyanidin-3-O-glucoside is the primary pigment responsible for the black or purple colour, early season 'Hass' show a poor colour development due to glucose competition between the seed and the exocarp, affecting the accumulation of anthocyanin. Objective colour measurements using the chromameter CIELAB system have provided quantitative insights into these changes.

Colour development may differ across different growing conditions, highlighting the role of orchards climate and postharvest handling in influencing the final pigmentation. While existing research has been conducted on 'Hass' , limited studies exist on hybrid cultivars like 'Carmen-Hass' and 'Maluma-Hass' on early season fruit, which may show different ripening characteristics. Therefore, further investigations into these cultivars are necessary to understand their colour development patterns and to optimize postharvest strategies for improved fruit quality and marketability.

CHAPTER 3: METHODOLOGY AND ANALYTICAL PROCEDURES

3.1. Production area and harvest time

The early-season ‘Hass’ avocado Hass fruit were harvested from a commercial farm in Tzaneen, ZZ2 Moeketsi Farm (23˚ 34’ 46.2850’’ S 3˚ 8’ 36.6148’’ E), Limpopo province, South Africa, at different times. Both 'Maluma-Hass' and 'Carmen-Hass' were harvested in April 2024, while traditional ‘Hass’ was harvested in May 2024. The Moisture levels in the fruit were ranging between 77-80%. The orchards followed uniform management practices. After harvesting, the fruit were transported to the laboratory at the University of Limpopo (23.886° S, 29.718° E) for sorting and stored in a cold room at 5.5˚C for 28 days. Following the cold storage phase, fruits were ripened at ambient temperature.

3.2. Experimental design

The experimental design used was a Completely Randomized Design (CRD) in a factorial arrangement with 3 (cultivars) × 7 (ripening days) replicated three times. The cultivars were ‘Hass’, 'Maluma-Hass' and 'Carmen-Hass'. The ripening evaluation days were 0,2,4,6,8,10 and 12.

3.3. Dry matter determination

The avocado fruit from three cultivars were peeled off using a knife to remove the exocarp. The mesocarp of the fruit was grated in a dish. A 10 g sample of the grated mesocarp was weighed and placed in an oven at 37°C for three days until it was evenly dried and weighed again. The dry matter content was calculated using the following formula (Brahmakshatriya and Donker, 1971):

Dry matter content = $(\frac{Dry\ weight}{Fresh\ weight}) * 100$

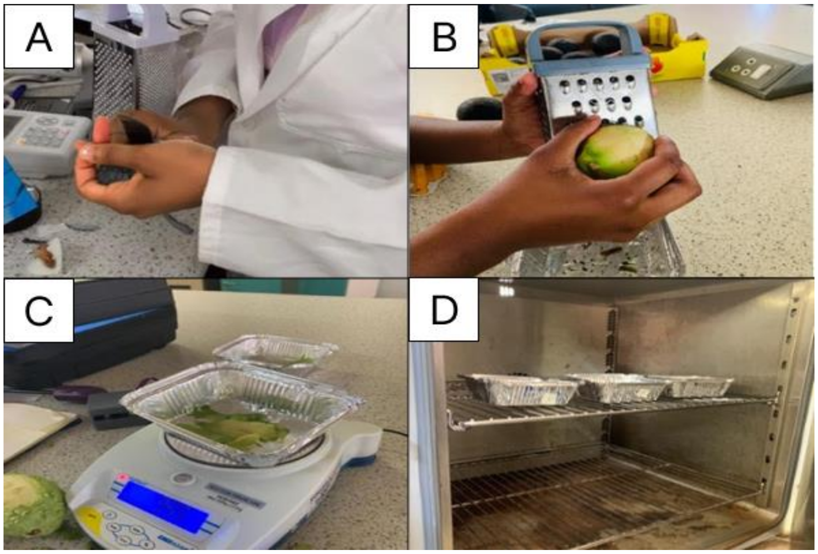


Figure 3.1 Determination of dry matter content in 'Hass' avocado fruit (A-Peeling, B-Grating, C-Weighing, D- Oven drying)

3.4. Determination of exocarp colour of the fruit

After the fruit were removed from cold storage, their exocarp colour was assessed both subjectively and objectively during ripening. On every evaluation day, three fruit were randomly selected for the assessment. Subjective assessment involved the use of the following scales: 1= emerald green, 2 = forest green, 3 = olive green, 4 = violet; and 5= purple and 6 = Black. Subsequently, the same fruit were subjected to objective measurements using a chromometer. The data obtained from the chromameter were presented as L*, a*, b*, C*, and $h°$ units. The L* is defined as darkness and lightness, where L*=0 represents black, and L*=100 represents white. The value of a* indicates the degree of redness when positive (+a*) and greenness when negative (− a*). The b* value indicates the degree of yellowness, whereas the C* value represents colour saturation. Additionally, h˚ denotes the basic colour, with 0° indicating red, 90° referring to yellow, 180° indicating bluish-green, and 270° corresponding to blue. The hue angle and chroma were calculated using the formula given by McGuire (1992).

Hue angle (h˚) = 180˚ + [tan (a* /b*)] …………………………………… (a)

Chroma (c)= $\sqrt{(a*)^2 + (b*)^2}$…………………………………………….....(b)

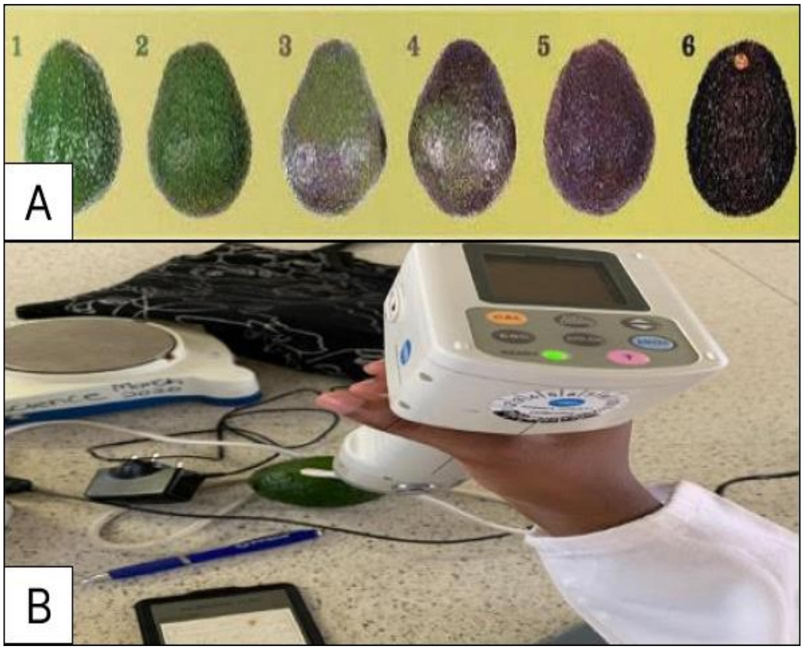


Figure 3.2 Measurements of colour using subjecting and objective measurements (A= Visual colour ranting, B= colour measurement using chromameter) in ‘Hass avocado

3.5. Determination of firmness

Fruit firmness was determined using a penetrometer. A section of the exocarp was removed with a fruit peeler to ensure direct contact with the flesh of fruit flesh. The penetrometer plunger was then pressed onto the exposed fruit surface until penetration occurred. The penetrometer was measured in pounds (lb) and in kilograms (kg). The readings were converted into Newtons (N). The readings ranged from 100 (hardness) to 0 (softness). The fruit was considered ripe when it reached a value of 14-8N.

Figure 3.3 Firmness determination using penetrometer on ‘Hass’ avocado fruit

3.6. Determination of external chilling damage

The external chilling damage was assessed upon the removal from cold storage using a rating scale of 0 to 3. The rating scale was expressed in 0= no chilling symptoms, 1= minimal chilling symptoms and 3= severe chilling symptoms (Albornoz *et al*., 2019). The external chilling index was calculated using the following formula:

Chilling Index (CI) = $\frac{(Chilling\ injury\ level)(Number\ of\ fruit\ at\ chilling\ level)}{(Total\ number\ of\ evaluated\ fruit\ )}$

3.7. Data analysis

The Genstat 18th edition software was used to perform the analysis of variance and the Pearson correlation was used to assess the correlation between colour development and softening. Mean separation was determined using Duncan’s multiple range test at P< 0.05.

CHAPTER 4: RESULTS AND DISCUSSION

4.1. Results

4.1.1. Dry matter (DM) content

The percentage of dry matter in three different avocado cultivars ‘Hass’, 'Carmen-Hass' and 'Maluma-Hass' at harvest is presented in Figure 4.1.1. The results showed that there was no significant difference ($p > 0.05$) in dry matter content between the three cultivars at harvest. The dry matter content for ‘Hass’ was approximately 21%, while 'Carmen-Hass' had the highest dry matter content among the three cultivars at approximately 26%. Meanwhile, 'Maluma-Hass’ cultivar had a dry matter content of roughly 22%, which was comparable to ‘Hass’, however this difference was not statistically significant.

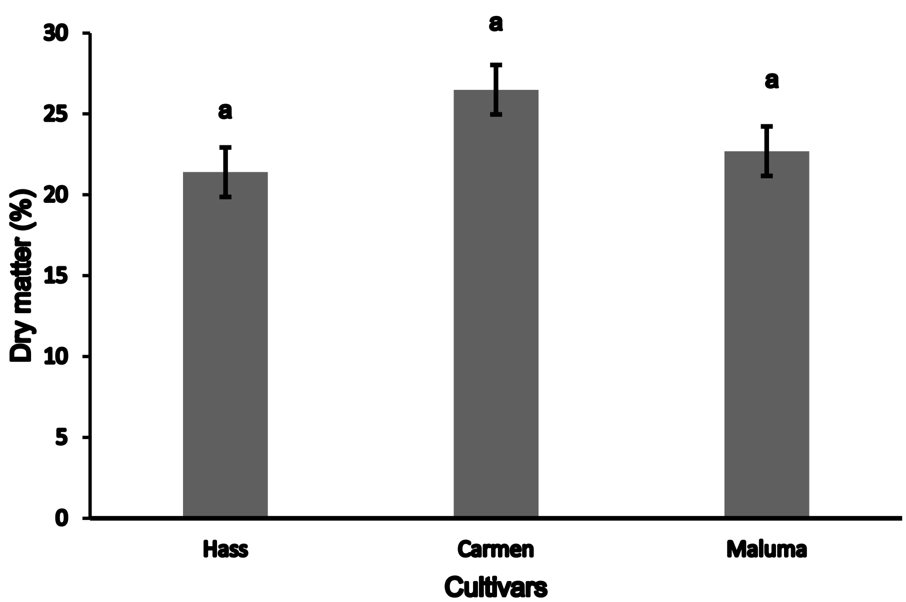


Figure 4.1 The measurement of dry matter content for the ‘Hass’, 'Carmen-Hass', and 'Maluma-Hass' avocado cultivars. Values represent the means of three fruit (n=3). The same letter above the error bars indicates no significant difference according to the LSD value at $p > 0.05$

4.1.2. Exocarp colour

Visual colour

The results indicated that exocarp visual colour (VC) was significantly affected by both the cultivar and ripening days, as well as their interaction ($p < 0.001$) (Figure 4.2). A slight increase in the VC was observed in all cultivars from days 1 to 4 of ripening, however all cultivars remained emerald green (1 = VC). At day 6 of ripening, the 'Hass' cultivar exhibited a significantly higher VC (3 – olive green) when compared with 'Carmen-Hass' (2 –forest green) and 'Maluma-Hass' (2 – forest green). Furthermore, on day 8 of ripening, Hass' displayed a significantly higher visual colour (3.67) in comparison to 'Maluma-Hass' (3 - VC) although this difference was not significant when compared with 'Carmen-Hass'. Nonetheless, all cultivars were olive green in colour at this stage (Figure 4.3). Additionally, 'Carmen-Hass' exhibited the highest significant visual colour rating of 5.33 (black) compared to 'Maluma-Hass' (4 = VC) violet and 'Hass' (4) (violet) on day 10. On day 12 of ripening, the 'Carmen-Hass' cultivar had a significantly higher visual colour rating of 5.67 (black) compared with 'Maluma-Hass' (5 - black) and 'Hass' (4 -violet) (Figure 4.3).

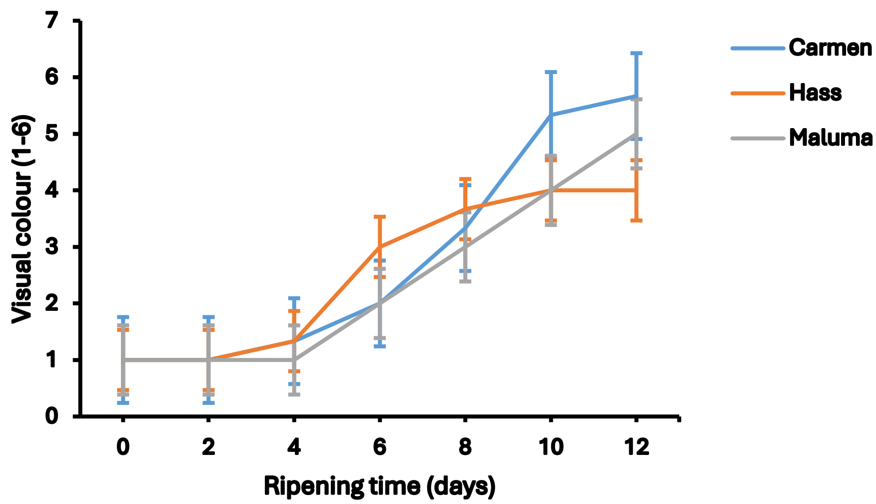


Figure 4.2 The changes in visual colour scores of 'Hass', 'Carmen-Hass', and 'Maluma-Hass' avocado cultivars over 12 ripening days. Values represent the means of three (3) fruit (n=3). The error bars represent ± SE of means at $p < 0.05$

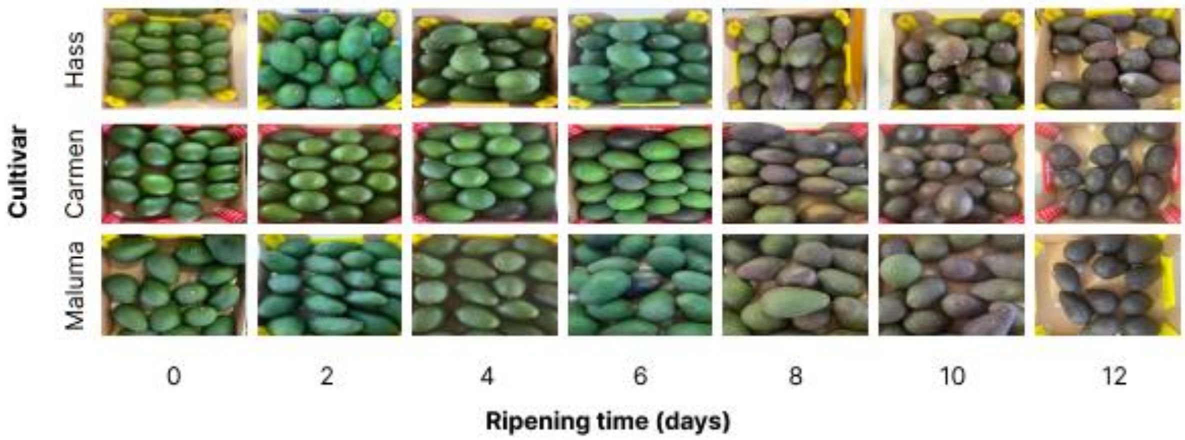


Figure 4.3 Changes in colour of the three cultivars of ‘Hass ', 'Carmen-Hass' and ‘Maluma-Hass' avocado cultivars during ripening

Lightness (L*)

The interaction between cultivar and ripening days was not significant ($p > 0.05$) on lightness (L*) during ripening (Figure 4.3). A slight decrease in lightness was observed for all cultivars on day 2 of ripening. Moreover, Hass’ and 'Carmen-Hass' showed a more pronounced decrease in L* values between day 2 and day 4 of ripening when compared to 'Maluma-Hass'. The L* values of all three cultivars converged at approximately 35 by day 6 of ripening. Furthermore, all three cultivars continued to show a decrease in L* values at a similar rate between days 6 and 8 of ripening. However, 'Carmen-Hass' showed a more rapid decrease in L* values between days 8 and 10, and then reached below 30 by day 12. Cultivars ‘Hass’ and 'Maluma-Hass' also showed a decrease in L* values, but ‘Hass’ maintained slightly higher lightness values compared to the other two cultivars by day 12.

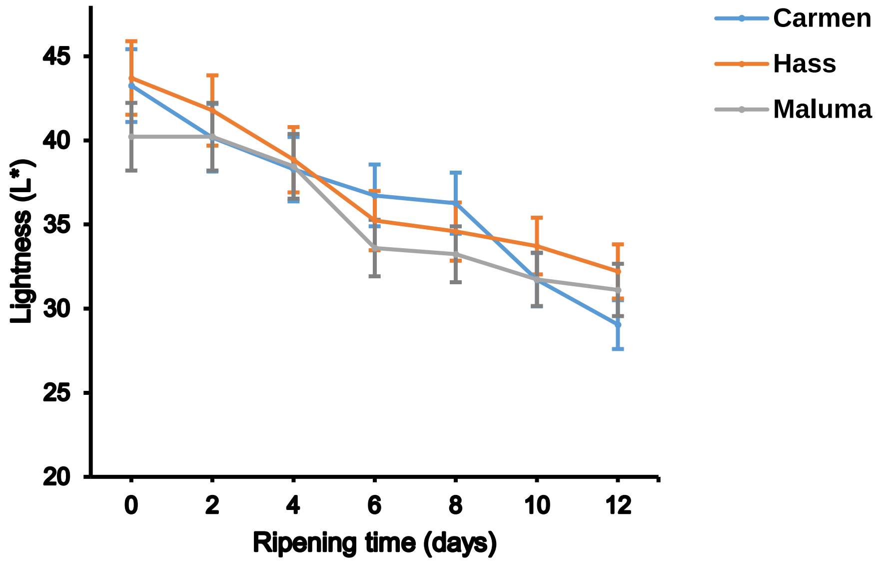


Figure 4.4 The changes in lightness (L*) values for ‘Hass’, 'Carmen-Hass', and 'Maluma-Hass' avocadp cultivars over a period of 12 ripening days. Values represent the means of three (3) fruits (n=3). The error bars represent ± SE of means at $p < 0.05$

Chroma

The interaction between cultivar and ripening days had a significant effect ($p < 0.05$) on the chroma (C*) values during ripening (Figure 4.1.4). At the beginning of the ripening period (day 0), ‘Hass’ cultivar showed the highest C* values around 12, while 'Carmen-Hass' and 'Maluma-Hass' started at lower C* values, around 5 and 3, respectively. During the early ripening days (days 2 - 4), ‘Hass’ cultivar maintained the highest C* values, although there was a noticeable decrease, whereas 'Carmen-Hass' and 'Maluma-Hass' showed an increase before starting to decline. By day 6, the C* values of ‘Hass’ and 'Carmen-Hass' become more comparable, converging around 6, while 'Maluma-Hass' continues to increase, reaching around 8. From days 8 to 12, all three cultivars show further declines in chroma, with 'Carmen-Hass' showing slight fluctuations wiath a pea around 5 by day 10. By day 12, the C* values of all three cultivars reached a similar point at around 2 with 'Maluma-Hass' slightly lower but following a similar pattern.

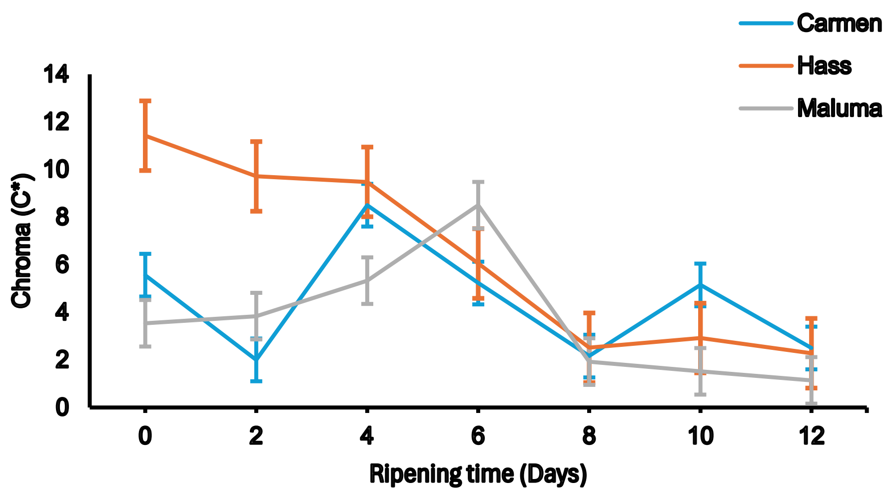


Figure 4.5 The changes in chroma (C*) values for 'Hass', 'Carmen-Hass', and 'Maluma-Hass' avocado cultivars over 12 ripening days. Values represent the means of three (3) fruits (n=3). The error bars represent ± SE of means at $p < 0.05$

a* value

The interaction between cultivars and ripening days showed a significant difference ($p < 0.05$) in the a* values during ripening (Figure 4.6). At the beginning of ripening (day 0), 'Carmen-Hass' avocados exhibit the highest a* values around -5, while 'Hass' and 'Maluma-Hass' started with a* values of -10 and-15. During the early ripening period (days 2-4), 'Carmen-Hass' maintained higher a* values around 2, while 'Hass' and 'Maluma-Hass' showed a slight decrease. By day 6, all cultivars increased with 'Carmen-Hass' and 'Hass' both having a higher a* value at around -3 while 'Maluma-Hass' had -6 b* value. By day 8, all three cultivars continued increasing, converging around 1. Between days 8 and 12, 'Carmen-Hass' and 'Hass' had a slight decrease at around -1 while 'Maluma-Hass' steadily increased at around 1. By day 12 all cultivars increased reaching a similar point around 1.

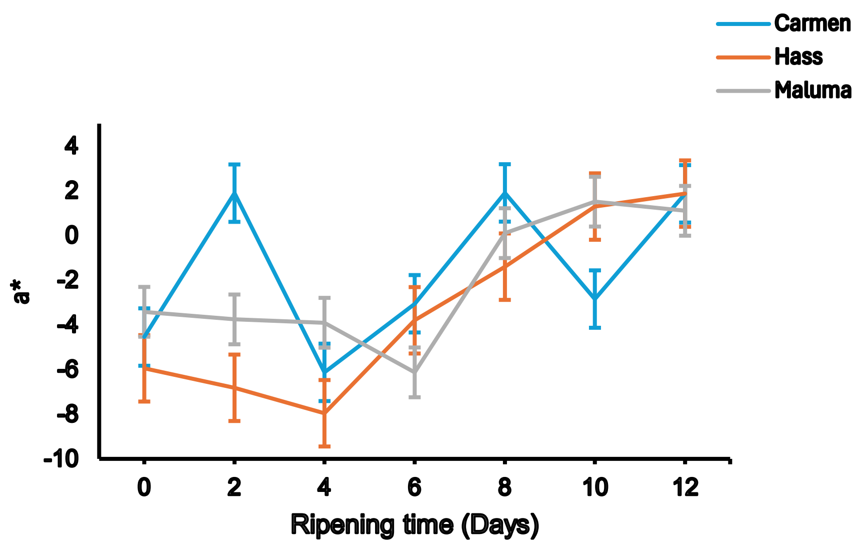


Figure 4.6 The changes in greenness (a*) values for ‘Hass’, 'Carmen-Hass', and 'Maluma-Hass' avocado cultivars over a period of 12 ripening days. Values represent the means of three (3) fruit (n=3). The error bars represent ± SE of means at $p < 0.05$

b* value

The interaction between cultivars and ripening days showed a significant difference ($p < 0.05$) in the b* values during ripening (Figure 4.7). At the beginning of ripening (day 0), Hass’ avocados exhibit the highest b* values around -5, while 'Carmen-Hass' and 'Maluma-Hass' started with b* values closer to 3 and 1. During the early ripening period (days 2-4), ‘Hass’ maintained higher b* values, while 'Carmen-Hass' showed a significant increase, and 'Maluma-Hass' remained relatively stable. By day 6, the b* values of 'Carmen-Hass' and ‘Maluma-Hass’ decreased significantly, converging around 5, while 'Hass' exhibited a more gradual decline, remaining around 2. From days 6 to 8, all three cultivars showed a notable decrease in b* values, with 'Carmen-Hass' dropping below 0, while 'Maluma-Hass’ and ‘Hass’ stabilised around 0. Between days 8 and 12, all three cultivars exhibited a further decrease in b* values, with 'Maluma-Hass' and 'Carmen-Hass' reaching values around -1, while 'Hass' showed a lower value at -3 by day 12.

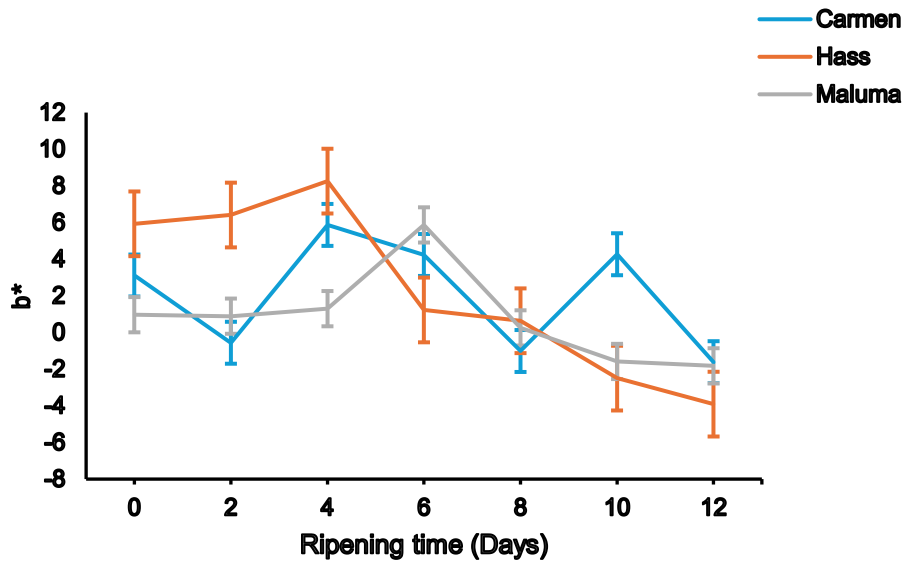


Figure 4.7 The changes in yellowness (b*) values for ‘Hass’, 'Carmen-Hass', and 'Maluma-Hass' avocado cultivars over 12 ripening days. Values represent the means of three fruit (n=3). The error bars represent ± SE of means at $p < 0.05$

Hue angle (h^o)

The interaction between cultivars and ripening days had a significant effect ($p < 0.05$) on hue angle (h^o) values during ripening (Figure 4.8). At the beginning of ripening (day 0), the 'Maluma-Hass' cultivar showed the highest h^o values, around 190, while ‘Hass’ and 'Carmen-Hass' begin with lower h^o values, around 150 and 180, respectively. During the early ripening period (days 2-4), 'Carmen-Hass' experienced a significant drop in h^o values to about 140, aligning closer to ‘Hass’, which also displayed decreasing trends but at a slower rate. By day 6, 'Maluma-Hass' and 'Carmen-Hass' exhibited similar h^o values of 130, while ‘Hass’ showed more variability with intermittent increase and decrease, indicating fluctuations in hue during this phase. After day 8, all cultivars showed a decrease in hue with ‘Hass’ and 'Carmen-Hass' maintaining lower h^o values close to 100 by day 12 as compared to 'Maluma-Hass' with minor fluctuations. During the late-ripening period (days 10-12), all three cultivars maintained h^o values close to 100, with minor fluctuations.

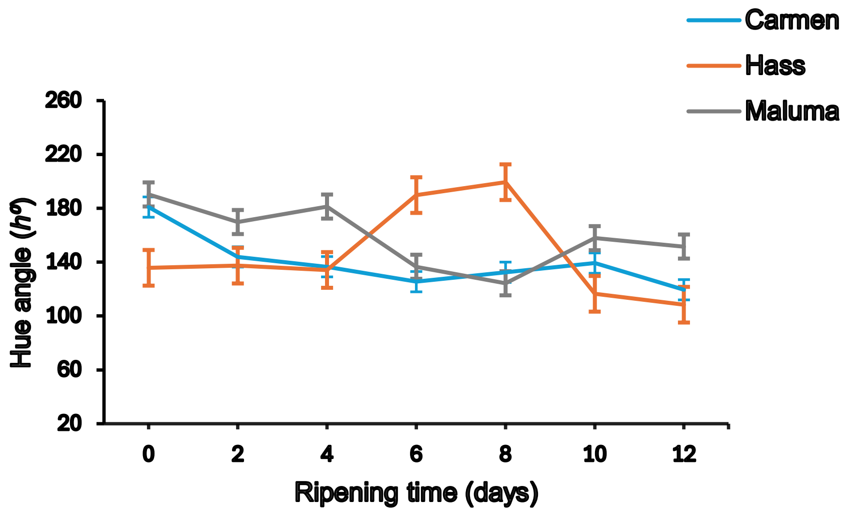


Figure 4.8 The changes in hue-angle (h^o) values for 'Hass', 'Carmen-Hass', and 'Maluma-Hass' avocado cultivar over a period of 12 ripening days. Values represent the means of three (3) fruit (3). The error bars represent ± SE of means at $p < 0.05$

4.1.3. Firmness

The interaction between cultivars and ripening day showed a significant effect ($p < 0.05$) on mesocarp firmness during ripening. Initially (day 0), all three cultivars started with high firmness values, around 70 for 'Hass' and 'Maluma-Hass', and slightly lower for 'Carmen-Hass' at approximately 60. During the early ripening period (days 2-4), 'Carmen-Hass' exhibited a more rapid decline in firmness, dropping to about 40, while 'Hass' and 'Maluma-Hass' maintained higher firmness values around 60 and 50, respectively. By Day 6, 'Carmen-Hass' continued to soften, reaching firmness values below 30, whereas 'Hass' and 'Maluma-Hass' show a more gradual decrease to around 40 and 50, respectively. From days 6 to 8, Hass' experienced a sharp decline in firmness, converging with 'Carmen-Hass' around 20, while 'Maluma-Hass' showed a more gradual decreased, maintaining firmness around 40. In the late ripening period (days 8-12), Hass' and 'Carmen-Hass' continued to soften significantly, reaching firmness values close to 0 by day 12. In contrast, 'Maluma-Hass' retained higher firmness values throughout the period, at around 20 by day 12.

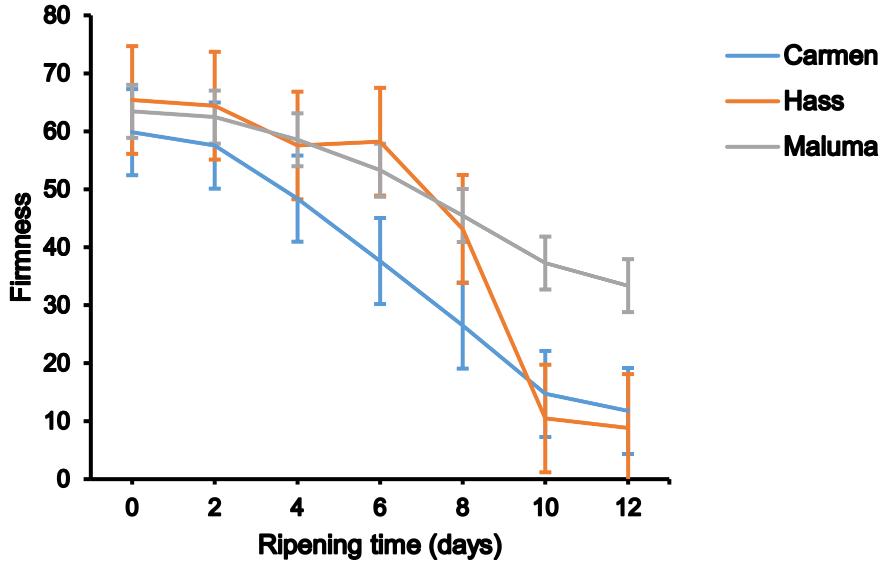


Figure 4.9 The measurements of fruit firmness for ‘Carmen-Hass', and 'Maluma-Hass' avocado cultivar over 12 ripening days. Values represent the means of three fruit (n=3). The error bars represent ± SE of means at $p < 0.05$

4.1.4. Pearson correlation coefficient

Table 4.1 shows Pearson correlation coefficient between objective colour (L*, a*, b*, C* and *h*º) and visual colour of three ‘Hass’ avocado cultivars with firmness for 12 days ripening period. For ‘Hass’, firmness was highly negatively correlated with visual colour (R= -0.942, $p < 0.01$), indicating that as firmness decreased, the visual colour increased (Table 4.1). A strong positive correlation was found between firmness and L* (lightness) (R= 0.819, $p < 0.01$). There was a strong negative correlation between firmness and a* (red/green) (R = -0.796, $p < 0.01$). However, the correlations between firmness and b* (R= 0.459), firmness and C* (R= 0.658) and firmness and *h*° (R= 0.377) were not significant.

For 'Carmen-Hass', the correlation between firmness and visual colour was also highly negative (r = -0.942, p< 0.001), demonstrating a significant change in visual colour as firmness decreased during ripening. Firmness showed a very strong positive correlation with L* (R= 0.859, $p < 0.001$) and a strong negative correlation with a* (R= -0.904, $p < 0.001$). Firmness is positively correlated with b* (R= 0.819, $p < 0.001$), C* (R= 0.790, $p < 0.001$) and *h*° (R= 0.623, p< 0.01).

For 'Maluma-Hass', similar to ‘Hass’, there was a highly negative correlation between firmness and visual colour ($r = -0.942$, $p < 0.01$) during ripening. Firmness was strongly positively correlated with L* ($r = 0.819$, $p < 0.01$) and negatively correlated with a* (R= -0.796, $p < 0.01$). The correlations between firmness and b* ($r = 0.459$) and firmness and C* (R= 0.658) were not significant during ripening. In general, a significant positive correlation existed between firmness and *h°* ($r = 0.690$, $p < 0.001$) during ripening of fruit.

Table 4.1 Pearson correlation coefficient between objective colour (*L*, a*, b*, C** and *hº*) and visual colour of ‘Hass’, 'Carmen-Hass' and 'Maluma-Hass' avocado cultivars with firmness over 12 ripening days

Correlation variables	‘Hass’	‘Carmen-Hass’	‘Maluma-Hass’
Firmness x visual colour	-0.942**	-0.942***	-0.942**
Firmness x L*	0.819**	0.859***	0.819**
Firmness x a*	-0.796**	-0.904***	-0.796**
Firmness x b*	0.459^{ns}	0.819***	0.459^{ns}
Firmness x C*	0.658^{ns}	0.790***	0.658^{ns}
Firmness x *h°*	0.377^{ns}	0.623**	0.690***

Significant difference is indicated by *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ and ns= not significant

4.1.5. Chilling injury

The chilling injury index in three different avocado cultivars is presented in Figure 4.10. The results showed that there was a statistically significant difference ($p< 0.05$) in external chilling index among the three cultivars at harvest. ‘Hass’ had the highest chilling index at approximately (1.8), while 'Carmen had external chilling index of roughly (1.7). Meanwhile 'Maluma-Hass' had the lowest external chilling index of about 1.3.

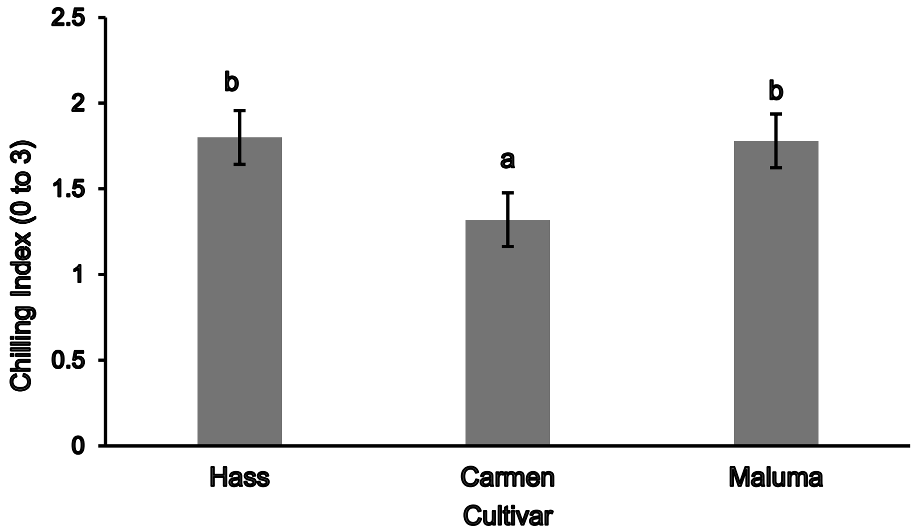


Figure 4.10: The measurement of external chilling index for ‘Hass’, 'Carmen-Hass', and 'Maluma-Hass' avocado cultivars. Values represent the means of three (3) fruit (n=3). The letters above the error bars indicate a significant difference according to the LSD value at $p < 0.05$

4.2. Discussion

4.2.1. Dry matter content (DMC)

The findings of this study indicated that while there were observable differences in dry matter content among the three avocado cultivars, these differences were not statistically significant (Figure 4.1). In terms of maturity, this suggested that the three cultivars were relatively similar at the time of harvest. The observed dry matter content of the three cultivars complied with the minimum standard for harvesting ‘Hass’ avocados in South Africa, ensuring consumer satisfaction and compliance with export quality standards (Hernández *et al*., 2016). Their similarity in DMC suggest that maturity was not a primary factor contributing to the observed differences in the exorcarp colour development among the three cultivars. Instead, the variation in postharvest colour development and softening may be attributed to genetic differences influencing anthocyanin synthesis and fruit physiology during ripening rather than differences in harvest maturity.

could suggest that the three cultivars were subjected to similar environmental conditions and similar harvest times. All the cultivars had DMC of less than 30%, meaning that they were all harvested at the early-season. Therefore, since there were no significant differences in the DMC among the cultivars, we conclude that this factor may not have an effect on the variability in colour development among the three cultivars.

4.2.2. Exocarp colouration

Visual colour (VC)

This study found that the exocarp visual colour (VC) of avocado fruit was significantly influenced by both the cultivar and ripening duration, as well as their interaction ($p < 0.001$; Figure 4.2). These results emphasized the importance of genetic and temporal factors in shaping the visual attributes of avocado fruit exocarp (Kamper *et al*., 2021). During the first four days of ripening, all cultivars showed a slight increase in VC, however remained emerald green, indicating that the initial stages of ripening did not significantly distinguish the cultivars in terms of VC. This finding aligned with previous studies showing gradual colour development in ‘Hass’ avocados with ripening days (Cox *et al*., 2004; Shikwambana *et al*., 2021; Sibeko *et al*., 2024). Significant differences emerged by day 6, with ‘Hass’ showing a higher VC (3 = olive green) than 'Carmen-Hass' and 'Maluma-Hass' (both at VC 2 = forest green). This indicated unique ripening characteristics in ‘Hass’, likely due to its genetic makeup which influenced a quicker change in colour. However, all cultivars reached an olive-green stage, suggesting a consistent and gradual colour change as they neared peak ripeness by day 8 (Bill *et al*., 2014). By day 10, 'Carmen-Hass' exhibited the highest VC (5.33 - purple), significantly outpacing ‘Maluma-Hass’ and ‘Hass’ (both at VC 4 - violet). This suggested a faster ripening process for 'Carmen-Hass', potentially due to its genetic and physiological characteristics. The genetic relationship between 'Carmen-Hass' and ‘Hass’ possibly due to 'Carmen-Hass' being a somatic mutant of ‘Hass’ could contribute to their similar ripening behaviours (Kamper *et al*., 2021). On day 12, 'Carmen-Hass' maintained a significantly higher VC (5.67 - black), while 'Maluma-Hass' and ‘Hass’ were at VC 5 (black) and VC 4 (purple), respectively. The accelerated colour development in 'Carmen-Hass' may be linked to factors such as anthocyanin distribution and synthesis, influenced by cell size, type, and sucrose concentration (Li and Ahmmend, 2023; Giuggioli *et al.*, 2021; Bayram and Tepe, 2020; Shikwambana *et al*., 2021). Although these cultivars could be genetically related, they differ in terms of their morphology. 'Carmen-Hass' fruit are usually smaller in size as compared to ‘Hass’ and 'Maluma-Hass' (Rosas *et al*., 2016). Smaller fruit usually have smaller cell size and a larger surface area (Shikwambana *et al*., 2021), therefore resulting in a higher concentration of anthocyanin responsible for the black colour in 'Carmen-Hass' fruit.Despite their genetic similarities, these findings confirms that ‘Hass’ change colour at a much slower rate than 'Carmen-Hass' but similarly to 'Maluma-Hass'.

Objective colour parameters (lightness -L*, chroma- C*, hue angle - *h*°, b* and a*)

In this study, the objective colour parameters; chroma (C*), hue angle (*h*°), and both a* and b* values were significantly influenced by the cultivar, ripening days, and their interaction ($p < 0.05$, Figure 4.4 – 4.8), while it was not for lightness (L*) ($p > 0.05$, Figure 4.4). All three cultivars displayed a decrease in L*, C*, *h*°, and b* values during ripening, while a* values increased (Figure 4.1.6). The decrease in L* values across all cultivars indicated a change in colour from lighter to darker, primarily due to the degradation of chlorophyll, the pigment responsible for the green colour in unripe fruit. As ripening progresses, chlorophyll breaks down, resulting in lower L* values, which was consistent with findings by Sibeko *et al*. (2024). Notably, 'Carmen-Hass' exhibited a more pronounced decline in L* values between days 2 and 4, and by day 12, ultimately reaching the lowest L* values among other cultivars by day 12 of ripening. These findings were consistent with those of Sibeko *et al.* (2024), who observed that prolonged ripening led to significant chlorophyll degradation and increased anthocyanin synthesis, resulting in lower L* values.

Chroma (C*), a measure of colour saturation, consistently declined as ripening progressed across all cultivars. Initially, ‘Hass’ had the highest C* values, indicating the most intense colour. However, all cultivars exhibited similar C* values, and by day 12, these values had further declined to approximately 2, with 'Maluma-Hass' showing slightly lower values by day 4 (Figure 4.5). This observation aligned with the findings of Nour *et al*. (2015) and Sibeko *et al*. (2024) who found that the intense green colour in early ripening stages of ‘Hass’ avocado was primarily attributed to chlorophyll content. Thus, the decline in C* showed a loss in colour intensity during ripening, attributable to the breakdown of chlorophyll and the synthesis of other pigments, such as carotenoids and anthocyanin, which were responsible for the colour changes in ripe avocados (Cox *et al*., 2004; Ozturk *et al*., 2016; Küçüker and Öztürk, 2015). The initially high C* values in 'Hass' suggested a higher concentration of chlorophyll, contributing to its intense green colour in the early stages of ripening (Nour *et al*., 2015).

The a* values, representing the red-green colour component, increased across all avocado cultivars during ripening. 'Hass' began with the lowest a* value of approximately -6, indicative of a skin greener colour. During ripening, 'Carmen-Hass' exhibited the highest increase in a* values, reaching around 2 by day 12, while 'Hass' and 'Maluma-Hass' were at 1 (Figure 4.1.6). The increase in a* values corresponds to the enzymatic degradation of chlorophyll and the accumulation of pigments like anthocyanin in fruit (Li *et al*., 2012). The significant increase in a* values for 'Carmen-Hass' suggested that this cultivar had a more pronounced capacity for anthocyanin synthesis compared to 'Hass' and 'Maluma-Hass', resulting in a more purple colouration as it ripens (Liu *et al*., 2017).

Regarding b* values, which measure the yellow-blue colour component, initially 'Hass' had the highest b*values when compared with other cultivars, indicating a greater colour change. However, all cultivars showed a decrease in b* values, with both 'Hass' and 'Carmen-Hass' dropping below 0 by day 8 as ripening progressed (Figure 4.1.7). By day 12, both 'Hass' and 'Carmen-Hass' had reached b* values around -3, with 'Maluma-Hass' following a similar tendency. The decline in b* values could be attributed to a reduction in chlorophyll content and the potential increase in anthocyanin synthesis, which may contribute to the darker colouration of ripe avocados.

The hue angle (*h°)* is a critical parameter in assessing the colour changes that occur during the ripening of avocado cultivars (Cox *et al*., 2004). In the observed study, *h*° values consistently decreased across all cultivars during ripening, with 'Maluma-Hass' initially displaying the highest *h*° values at around 180, indicative of intense green colouration. By day 6, all 'Carmen-Hass' and 'Maluma-Hass' had similar *h*° values of approximately 130, and by days 8-12, these values became constant near 100 (Figure 4.1.6). This reduction in *h*° values indicated a change towards darker colour (purple/black) change which was in line with previous studies (Cox *et al*., 2004; Ashton *et al*., 2006; Shikwambana *et al*., 2021). The initial higher *h*° values in 'Maluma-Hass' indicated intense green exocarp colouration during the early ripening stages, which may be due to high chlorophyll content in avocadoes. As ripening progresses, the degradation of chlorophyll leads to a reduction in *h*° values (Ashton *et al*., 2006). The steadiness of *h*° values around 100 by days 8-12 suggested that the ripening process reached a common endpoint across different cultivars (Cox *et al*., 2004).

4.2.3. Firmness

The rapid decline in firmness observed in 'Carmen-Hass' during the early ripening period suggested that this cultivar ripened more quickly than ‘Hass’ and 'Maluma-Hass'. In contrast, 'Maluma-Hass' exhibited more gradual softening, indicating that it may have a longer shelf-life or delayed ripening characteristics. This suggested a potential advantage for 'Maluma-Hass' in postharvest handling and marketing. Previous studies have also reported faster ripening rates in 'Carmen-Hass' than in 'Hass (Kamper *et al*., 2021) which supported the findings of the present study

The more rapid softening of 'Carmen-Hass' may be attributed to its lower initial firmness and higher ethylene sensitivity, which lead to accelerated ripening. In contrast, the slower rate of firmness decline in 'Maluma-Hass' may be related to its thicker skin or lower ethylene sensitivity, which could delay the ripening process. One limitation of this study was that it only measured firmness as an indicator of ripening. Other factors, such as internal composition changes including ethylene production, cell wall degradation, respiration rate, enzyme activities and changes in phenolic compounds (Barry, 2010) were not assessed but may offer a more comprehensive understanding of ripening behaviour. The rapid ripening of 'Carmen-Hass' suggests that this cultivar may be better suited for markets that require quick consumption, whereas the delayed softening of 'Maluma-Hass' indicates its potential for extended shelf life, making it more suitable for export and long-term storage. Future studies should investigate the biochemical factors that contribute to the slower ripening of 'Maluma-Hass' and explore methods to further extend the shelf life of all cultivars through postharvest treatments.

4.2.4. Pearson correlation coefficients

In ‘Hass’ fruit, the highly negative correlation between firmness and visual colour (R= -0.942, $p < 0.01$) indicated that as the fruit ripened and softened, its visual colour changed significantly during ripening. The positive correlation between firmness and L* (R= 0.819, $p < 0.01$) suggested that brighter green-coloured fruit were firmer, while the negative correlation with a* (R= -0.796, $p < 0.01$) indicated a change towards purple colour as the fruit softened during ripening. The stronger negative correlation between firmness and visual colour (R= -0.942, $p < 0.001$) in 'Carmen-Hass' further highlighted a rapid visual change during ripening. The strong positive correlation between firmness and L* (R= 0.859, $p < 0.001$) and negative correlation with a* (R= -0.904, $p < 0.001$) suggested a rapid loss of lightness and greenness as the fruit softened. Like ‘Hass’, 'Maluma-Hass' exhibited a highly negative correlation between firmness and visual colour (R= -0.942, $p < 0.01$), and a strong positive correlation with L* (R= 0.819, $p < 0.01$), indicating a similar pattern of colour change during ripening. While all three cultivars showed a significant negative correlation between firmness and visual colour, the strength of these correlations varied slightly. 'Carmen-Hass' exhibited the strongest correlation between firmness and a* (R= -0.904, $p < 0.001$), indicating a more pronounced colour change from green to purple during ripening compared to ‘Hass’ and 'Maluma-Hass'.

In contrast, ‘Hass’ and 'Maluma-Hass' showed similar patterns in their correlations with L* and a* values. The observed negative correlation between firmness and visual colour aligns with previous studies that indicate a significant visual change in avocado colour as firmness decreased during ripening (Cox *et al*., 2004; Shikwambana *et al*., 2021; Sibeko *et al*., 2024). Similarly, the positive correlation between firmness and L* has been widely reported in avocado fruit, suggesting that firmer avocados tend to have a lighter green colour (Shikwambana *et al*., 2021). The differences observed between 'Carmen-Hass' and the other cultivars may be attributed to its faster ripening process and higher ethylene sensitivity, leading to more rapid changes in both firmness and colour. The more gradual change in 'Maluma-Hass' may be due to its thicker skin, which could slow down the ripening process and delay the associated colour changes. One limitation of this study is the reliance on visual colour assessments, which may introduce some subjectivity into the analysis. Additionally, measuring more cultivars could provide a broader understanding of the relationship between firmness and colour across avocado varieties. Understanding the correlation between firmness and colour during ripening is crucial for avocado growers and distributors to determine optimal harvest and storage times. The stronger correlations in 'Carmen-Hass' suggest it may require more careful monitoring during ripening, while 'Maluma-Hass' may be better suited for extended storage. Future research could explore the underlying biochemical mechanisms that drive the rapid colour changes observed in 'Carmen-Hass', as well as investigate how these relationships might vary under different storage conditions or with different ripening agents.

4.2.5. Chilling Injury Index (CII)

The measurement of the external chilling index for three avocado cultivars is presented in Figure 4.10. The study revealed that 'Carmen-Hass' exhibited the lowest chilling injury index (1.3) compared to 'Hass' (1.8) and 'Maluma-Hass' (1.7), showing a statistically significant difference ($p < 0.001$, Figure 4.1.10). In 'Carmen-Hass', the lower CII suggested that it is more resistant to external chilling damage than the other cultivars. This could be attributed to differences in moisture content, which has been linked to susceptibility to chilling injury (Abass *et al*., 2020). These findings are consistent with previous studies which reported that fruits with higher moisture content are more prone to chilling injury, as the excess water leads to increased cellular damage when exposed to low temperatures (Mathur *et al*., 2021; Hu *et al*., 2022). However, the role of moisture content, as suggested by our study, aligned with those of Hu *et al*. (2022), who demonstrated that higher moisture content in fruits can exacerbate chilling injury, as excess water may lead to physiological stress during cold storage. One possible explanation for the lower chilling index observed in 'Carmen-Hass' may be its maturity level specifically sugar accumulation, which could buffer the effects of chilling.

The higher moisture content in 'Hass' and 'Maluma-Hass' might have made these cultivars more vulnerable to external chilling damage, as evidenced by the increased CII. It is important to note that while moisture content appears to influence the chilling index, other factors such as ethylene sensitivity, and biochemical composition post-harvest treatment may also play a role, which were not fully explored in this study. These results suggested that 'Carmen-Hass' is more suitable cultivar for extended cold storage, potentially reducing postharvest losses compared to ‘Hass’ and 'Maluma-Hass' . These findings also contribute to the growing body of knowledge on avocado cultivar resilience, particularly under cold storage conditions. Future research should investigate the genetic factors influencing moisture content and chilling resistance among avocado cultivars to confirm these findings and to further explore post-harvest treatments.

CHAPTER 5: SUMMARY AND CONCLUSION

5.1. Summary

This study aimed to evaluate the postharvest exocarp colour development in three Hass avocado cultivars and their correlation with softening. The Hass-type avocado fruit were subjected to cold storage to simulate export conditions for 28 days and thereafter ripened for a period of 12 days. Dry matter content was measured at harvest and the chilling injury index was measured upon withdrawals from cold storage. Furthermore, visual colour and objective colour parameters (L*, a*, b*, C* and *h*°) were measured alongside firmness throughout the 12-day ripening period. The findings of the study showed that 'Carmen-Hass' had the highest dry matter content as compared with other cultivars and exhibited a significant change in visual colour and objective colour parameters. All cultivars experience a decline in firmness with 'Carmen-Hass' and ‘Hass’ softening rapidly while 'Maluma-Hass' retained its firmness the longest. Firmness was negatively correlated with visual colour in all cultivars, with 'Carmen-Hass' exhibiting the strongest correlation. Furthermore, a strong positive correlation between firmness with L*, a*, b* and C* in 'Carmen-Hass' indicated a change to a darker colour as the fruit was ripening. Therefore, the study highlighted the differences in ripening and colour change patterns among the three avocado ‘Hass’ cultivars, with 'Carmen-Hass' exhibiting the most significant change from green to purple/black colour. Moreover, all cultivars were susceptible to chilling damage during cold storage with 'Carmen-Hass' exhibiting lower chilling damage as compared to other cultivars.

5.2. Conclusions

This study confirms that ‘Hass’ exhibits different exocarp colour development compared to 'Carmen-Hass' and ‘Maluma-Hass'. The cultivar type and ripening days had an effect on the colour development and ripening behaviour of the three Hass avocado cultivars. While all cultivars followed the same general ripening pattern, 'Carmen-Hass' had the most significant change in colour and ripened more rapidly indicating a more improved colour change as compared to 'Maluma-Hass' and Hass. 'Maluma-Hass', ripened much slower, retained its firmness the longest, and exhibited delayed colour changes, while ‘Hass’ had poor colour development. Additionally, the findings of this study revealed a positive correlation between softening and colour development in ‘Hass’ avocado cultivars, indicating that as the fruit’s colour changes during ripening, the rate of softening increased.

Furthermore, the improved colour development in 'Carmen-Hass' and 'Maluma-Hass' could be attributed to their smaller fruit and size compared to ‘Hass’, also their physiological characteristics of having a thicker skin that allows for a high distribution of anthocyanin. Although 'Maluma-Hass' developed a purple colour, it experienced variability in colour change in its consignment, while 'Carmen-Hass' had a uniform colour change during ripening. Moreover, the differences observed in their colour change and softening across all cultivars suggest that they behave differently in postharvest conditions. Therefore, this suggests that 'Carmen-Hass' has the potential to be exported early, given proper handling

5.3. Recommendation and future studies

The study revealed that 'Carmen-Hass' had improved colour development as compared to ‘Hass’ and 'Maluma-Hass'. Therefore, it may be recommended and suitable for early export and quick consumption markets due to its fast-ripening rate. However, it will not replace ‘Hass’ instead it will be offered as an early export while ‘Hass’ is still maturing. Future studies could focus on investigating the effect of genetic variation and postharvest treatments among the three cultivars on exocarp colour development.

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